Exploiting selection diversity in communications systems with non-orthonormal matrix and vector modulation

Field of the invention
The invention relates to a method for scheduling at least one out of K transmission channels k with respective $N_{t,k}$ transmission interfaces and respective $N_{r,k}$ reception interfaces for the transmission of data symbols modulated according to a non-orthonormal matrix or vector modulation.

Background of the invention
In the context of a wireless communication system, as for instance the Universal Mobile Telecommunications System (UMTS), scheduling can be formulated in terms of a preference function f_k that is calculated for at least one transmission channel out of $k=1,..,K$ transmission channels for a block of substantially orthogonal resources (e.g. frequency, subcarriers, spreading codes, time slots, spatial/polarization eigenmodes) to be scheduled simultaneously. The transmission channel or channels that have the largest value of f_k, or a value of f_k that is above some pre-defined limit are used for transmitting data using the scheduled resources. In this context, a transmission channel k may for instance describe the physical propagation channel between a single- or multi-antenna transmitter and a single- or multi-antenna receiver. There may be only one or several transmitters, and, correspondingly, there may be one or several receivers. Said transmitters and receivers may represent base stations, mobile stations or relay stations of a wireless communication system. A transmission channel k can be defined for both the up-

and downlink. A transmission channel k may further relate
to a channel between only a sub-group of transmit antenna
elements of a multi-antenna transmitter and a single- or
multi-antenna receiver, or to a channel between a single
or multi-antenna transmitter and a sub-group of antenna
elements of a receiver.

The preference function f_k for a transmission channel k
may be of the form:

$$f_k = f\ (u,\ d_k,\ z_k,\ h_k,\ c_k, CQIm_k, CQIe_k, CQIs_k,...)$$

Here, u is a parameter that describes the general status
of the transmission queue, and the remaining parameters
are specific for the transmission channel $k=1,..,K$. Thus
d_k is the delay experienced by transmission channel k,
i.e. the time that the next packet for/from transmission
channel k has spent in the queue, z_k is the size of the
next packet scheduled for her (or scheduled by her for
transmission, in uplink operation), h_k describes the
history, taking into account the amount of data
transmitted via transmission channel k during the
immediate past, and c_k is her possible priority class,
possibly based on the type of subscription or terminal,
and/or the type of data. The link-specific Channel
Quality Indicators (CQI) that scheduling may be based on,
are

• $CQIm_k$, which determines the transmission mode of
transmission channel k. The mode selection may be based
on side information, based on measurements at the
transmitter, or feedback from a receiver. In particular,
$CQIm_k$ determines the rate of transmission channel k, and
possibly the used feedback-based beamforming, the

Adaptive Space-Time Modulation scheme chosen
(matrix/vector modulation, space-time coding), the rate
of the concatenated channel code, and/or the modulation
alphabets.

- $CQIe_k$, which indicates the expected error rate of the
transmission mode indicated by $CQIm_k$, and

- $CQIs_k$, which indicates the speed of transmission channel
k, i.e. the channel coherence time.

Based on these parameters (or a subset of them), a
scheduler can decide which transmission channel is suited
for data transmission, taking into account overall
throughput, fairness, delays etc., when applicable. The
parts of f_k that do not depend on the radio link are the
domain of higher layer protocols. The CQIs, however, are
in intimate relationship to the physical layer, and are
to be designed in accordance to the physical layer
algorithms.

When considering the physical layer, the preference
functions f_k may be used in order to minimize the
transmission power, maximize the rate, or optimize
performance. Often, the physical and higher layer
algorithms involve an automatic retransmission request
(ARQ) protocol. In these cases, maximizing system
capacity typically requires that the frame or block error
rate is close to a given optimal value. Thus the
preference functions f_k may be used to choose the
transmission channel that provides the highest rate with
the maximum allowed transmission power, reaching a target
error performance.

If scheduling is based on $CQIe_k$, i.e. CQIs that correlate
with the expected error performance, the most clear cut
way to measure the performance of scheduling is to
measure the performance of selection diversity. This
means that a number K of transmission channels are
considered that have some type of channel statistics. Due
to this statistical nature of the K transmission
channels, scheduling for example one specific
transmission channel out of the K transmission channels
that actually has the optimum transmission channel
characteristics, for instance the lowest fading or path
loss, for data transmission achieves superior performance
as compared to transmitting on an arbitrarily chosen
transmission channel. Thus, as multi-user diversity is
available to a transceiver in a communication system with
multiple users to receive or transmit signals, or antenna
diversity is available to a receiver that deploys
multiple antenna elements to receive a signal that has
been transmitted by a transmitter using only a subset of
the multiple receiver elements or to transmit a signal
using only a subset of the multiple transmitter elements,
or frequency diversity is available when a signal is
transmitted at different portions of the available
channel bandwidth, selection diversity is available for
the scheduler when it is offered the degree of freedom to
choose from a variety of transmission channels between
different transceivers or their elements.

For optimal performance of selection diversity, the
transmission channel with the lowest predicted bit error
rate (BER) may be scheduled for transmission. This
results in a decreased average error rate. However, for a
Multiple-Input-Multiple-Output (MIMO) channel, scheduling

based on direct evaluation of BER requires heavy
computation.

Prior art document "On transmit diversity and scheduling
in wireless packet data" by A. G. Kogiantis, N. Joshi,
and O. Sunay, published in IEEEcomm, June 2001, vol. 8,
pp. 2433-2437, discloses scheduling in a Multiple-Input-
Single-Output (MISO) channel, wherein, among others, an
orthonormal diversity transmission scheme (Space-Time
Transmit Diversity, STTD) is compared to a single-antenna
transmission scheme without diversity. In both schemes, a
transmitter (either with two transmit antennas and STTD
or with a single antenna) schedules one out of K
transmission channels, wherein each respective
transmission channel is defined by the physical
propagation channel between the two or one transmit
antennas at the transmitter and the single antenna at the
respective receiver, for a data transmission, wherein
scheduling is based on the maximum Carrier-to-
Interference power ratio (C/I) for each transmission
channel.

The STTD scheme as deployed in the Kogiantis reference
can be considered as a matrix modulation scheme, which
may be defined as a mapping of modulation symbols onto
non-orthogonal spatial resources and orthogonal
resources, as for instance time slots or symbol periods,
frequency carriers, orthogonal codes, etc., or any
combination of these.

In matrix modulation schemes, diversity may be applied.
For instance, in a space-time matrix modulation scheme,
at least one of said modulation symbols may be mapped to
a first antenna element in a first symbol period and to a

second antenna element in a second symbol period.
Similarly, in a space-frequency matrix modulation scheme,
at least one of said modulation symbols may be mapped to
a first antenna element and transmitted with a first
carrier frequency and to a second antenna element and
transmitted with a second carrier frequency.

If modulation symbols are mapped to the non-orthogonal
spatial resources only, so-called vector modulation is
performed, and only spatial diversity is available.

In the sequel of this introduction, space-time matrix
modulation methods will be presented as an example of
orthonormal and non-orthonormal matrix modulation
methods. The orthogonal resource is then represented by
the T symbol periods (or time slots) to which a block of
data symbols is mapped. However, the presented matrix
modulation methods are readily applicable to matrix
modulation that employs the frequency domain, the code
domain, the eigenmode domain or polarization domain as
orthogonal resource instead of the time domain.

A space-time matrix modulator employing N_t transmit
antennas and T symbol periods is defined by a $T{\times}N_t$
modulation matrix X. The modulation matrix X is a linear
function of the Q complex-valued modulation symbols x_n,
$n=1,..,Q$ to be transmitted by the N_t-antenna transmitter
during T symbol periods. Modulation symbols may for
instance obey the Binary Phase Shift Keying (BPSK),
Quaternary Phase Shift Keying (QPSK) or Quadrature
Amplitude Modulation (QAM) symbol alphabet. The
modulation matrix X thus basically defines when
modulation symbols x_n with $n=1,..,Q$ and/or functions of
said modulations symbols x_n such as $-x_n$, x_n^* or $-x_n^*$ are

transmitted from which transmit antenna $n_t=1,..,N_t$ at which time instance $t=1,..,T$. In this context, the superscript operator "*" denotes the conjugate-complex of a complex number. The matrix modulation then can be understood as a mapping of modulation symbols and functions thereof to N_t respective data streams that are transmitted by N_t respective transmit antenna elements of a transmit antenna during T symbol periods. For the STTD scheme as applied in the Kogiantis reference, the modulation matrix X is defined according to the so-called Alamouti Space-Time code with $T=2$ and $N_t=2$ as

$$X = \begin{bmatrix} x_1 & x_2 \\ -x_2^* & x_1^* \end{bmatrix}. \tag{1}$$

With $N_{k,r}$ receive antennas at the reception side of the transmission channel k, the signal model reads as:

$$Y_k = X \cdot H_k + N_k, \tag{2}$$

wherein Y_k is a $T \times N_{k,r}$ matrix of signals $y_{k,ij}$ received at receive antenna element $j=1,..,N_{k,r}$ during symbol period $i=1,..,T$, wherein the elements $h_{k,ij}$ with $i=1,..,N_t$ and $j=1,..,N_{k,r}$ of the $N_t \times N_{k,r}$ channel matrix H_k define the flat fading propagation channel between transmit antenna element i and receive antenna element j, and wherein the $T \times N_{k,r}$ matrix $N_{k,r}$ represents the noise received in symbol period $t=1,..,T$ at receive antenna element $n_k=1,..,N_{k,r}$.

Lumping together the effects of matrix modulation as defined by the matrix X and the propagation effects as defined by the channel matrix H_k yields a complex-valued

$TN_{k,r} \times Q$ equivalent channel matrix G_k with an equivalent signal model:

$$y_k = G_k \cdot x + n_k ,\tag{3}$$

wherein the $TN_{k,r}$-dimensional vector y_k contains the signals received during T symbol periods at the $N_{k,r}$ receive antenna elements at the reception side of transmission channel k, or functions thereof such as the conjugate-complex receive signal, the negative receive signal or the negative conjugate-complex receive signal; the Q-dimensional vector x contains the Q complex-valued modulation symbols x_n, $n=1,..,Q$ that are modulated by the matrix modulation onto N_t transmit antenna elements in T symbol periods; and the $TN_{k,r}$-dimensional vector n_k contains the noise received at the receive antenna elements during the T symbol periods.

For the STTD scheme, the equivalent channel matrix G_k has the following shape:

$$G_k = \begin{bmatrix} h_{k,11} & h_{k,21} \\ h_{k,21}^{*} & -h_{k,11}^{*} \end{bmatrix} ,\tag{4}$$

and the equivalent system model reads as

$$\begin{pmatrix} y_{k,11} \\ y_{k,21}^{*} \end{pmatrix} = \begin{bmatrix} h_{k,11} & h_{k,21} \\ h_{k,21}^{*} & -h_{k,11}^{*} \end{bmatrix} \cdot \begin{pmatrix} x_1 \\ x_2 \end{pmatrix} + \begin{pmatrix} n_{k,11} \\ n_{k,21} \end{pmatrix} .\tag{5}$$

It is readily seen from equation (5) that both the effects of matrix modulation and channel propagation are now contained in the equivalent channel matrix G_k, so that

in the equivalent signal model of equation (5), the original modulation symbols x_n and not functions of the modulation symbols x_n are multiplied with the equivalent channel matrix G_k. With the equivalent channel matrix G_k, the Equivalent Channel Correlation Matrix (ECCM) R_k can be defined as

$$R_k = G_k^H \cdot G_k ,$$
                                                                 (6)

wherein the superscript operator "H" denotes the Hermitian conjugate of a matrix.

For the STTD scheme, it is easily seen that the ECCM is a diagonal matrix with

$$R_{k,STTD} = \begin{bmatrix} |h_{k,11}|^2 + |h_{k,21}|^2 & 0 \\ 0 & |h_{k,11}|^2 + |h_{k,21}|^2 \end{bmatrix} .$$

The ECCM can be interpreted as applying a matched filter to the equivalent channel matrix G_k, so that a matched filer estimate of the vector x that contains the Q modulation symbols x_n with $n=1,..,Q$ is obtained as

$$\hat{x} = G_k^H \cdot y_k = R_{k,STTD} \cdot x_k + G_k^H \cdot n_k.$$

When the power of the noise contribution n_k can be neglected as compared to the power of the receive signal y_k, the matched filter estimate $\hat{x}$ is basically given by the term $R_{k,STTD} \cdot x_k$, i.e. the matched filter estimates $\hat{x}_n$ are simply the modulation symbols x_n scaled by a real-valued factor $|h_{k,11}|^2 + |h_{k,21}|^2$ that is identified as the sum of the

powers of the channels $h_{k,ij}$ between the $i=1,..,N_t$ transmit
antennas and the $i=1,..,N_{k,r}$ receive antennas.

The ECCM according to the STTD matrix modulation scheme
only has non-zero entries on the main diagonal and thus
does not cause self-interference between modulation
symbols x_n in the matched filter estimates $\hat{x}_n$. Moreover,
the diagonal elements are all equal, thus the ECCM is
proportional to the identity matrix. Matrix modulation
schemes with ECCM proportional to the identity matrix
will be denoted as orthonormal matrix modulation schemes
in the sequel, whereas matrix modulation schemes with
ECCMs not proportional to the identity matrix will be
denoted as non-orthonormal matrix modulation schemes.

Figs. 1 and 2 show the essential features regarding
scheduling in a selection diversity setting with STTD as
disclosed in the Kogiantis reference. In particular,
scheduling performance is investigated with orthonormal
matrix modulation (STTD, $N_t=2$) and without matrix
modulation ($N_t=1$) for $N_{k,r}=1$ and different numbers of
transmission channels K, wherein the selection of a
transmission channel for a data transmission is based on
the maximum C/I at the reception side of that
transmission channel.

Fig. 1 shows the scheduling performance in terms of
$\log_{10}(\text{BER})$ as a function of the ratio E_b/N_0 of energy per
bit E_b and noise power density N_0 (assuming an Additive
White Gaussian Noise (AWGN) process at the reception side
of the transmission channel) in dB. Results for QPSK
modulation and independent identically distributed
(i.i.d.) flat Rayleigh-fading channels are depicted in
separate figures for $K = 1$, 2, 4 and 8 transmission

channels with (dashed line) or without STTD (solid line),
respectively.

It is observed that when there are up to $K = 4$
transmission channels, scheduling with STTD outperforms
scheduling without transmit diversity, because the
(uncoded) BER with STTD is significantly smaller than the
(uncoded) BER without STTD across the complete E_b/N_0
regime. However, for $K = 8$ transmission channels,
scheduling without STTD outperforms STTD-based scheduling
up to a BER 10^{-3}. In the high E_b/N_0 regime, the transmit
diversity of STTD still gives better performance.

The reason for this can be seen in Fig. 2, where
Probability Distribution Functions (PDFs) of the Signal-
to-Noise Ratio (SNR) at the scheduled receiver (with
Maximum Ratio Combining (MRC) for STTD) are plotted for
i.i.d. Rayleigh fading channels $h_{k,ij}$ with $E\{|h_{k,i1}|^2\} = 1$,
once again for the cases with (dashed line) and without
STTD (solid line) and for different numbers of
transmission channels $K=1, 2, 4$ and 8 among which
scheduling is performed. It can be clearly seen from the
reduced extension and the pronounced maxima of the PDFs
how STTD reduces the fluctuations in channel power. Also,
it is evident that STTD is not able to change the average
SNR of the channel, it just improves bad channels with
the price of making good ones worse. Thus a significant
portion of transmission channels, that have a strong
channel from one transmit antenna and a weak from the
other, have worse received SNR after MRC combining (see
Fig. 2, upper left corner). With an increasing number K
of transmission channels, a non-STTD transmission can
always be scheduled to a transmission channel that would
have had a worse channel if STTD was applied. Thus for

multiple transmission channels K, scheduling without STTD
works better.

The situation regarding combinations of orthonormal
matrix modulation (STTD) and scheduling as disclosed in
the Kogiantis reference can thus be summarised as:

• For more than $K=5$ transmission channels, orthonormal
matrix modulation (STTD) performs worse than a single
antenna transmission as a component in a selection
diversity scheme with max C/I-based scheduling, at BER
10^{-3}.

• If more than $K=3$ transmission channels are scheduled
simultaneously, STTD and other orthonormal matrix
modulations are of no practical use.

Summary of the invention
In view of the above-mentioned problems, it is thus an
object of the present invention to improve communications
systems that perform scheduling in combination with
matrix and vector modulation in a selection diversity
setting.

It is proposed a method for scheduling at least one out
of K transmission channels $k=1,..,K$ with respective $N_{t,k}$
transmission interfaces and respective $N_{r,k}$ reception
interfaces for the transmission of data symbols modulated
according to a non-orthonormal matrix modulation that
modulates data symbols in both a non-orthogonal spatial
domain and at least one orthogonal domain, wherein at
least one Equivalent Channel Matrix (ECM) G_k can be
defined that transforms said data symbols into data
symbols that have been matrix modulated, transmitted over

$N_{t,k}$ transmission interfaces and received at $N_{r,k}$ reception interfaces of one of said transmission channels $k=1,..,K$, and wherein an Equivalent Channel Correlation Matrix (ECCM) $R_k = G_k^H \cdot G_k$ of said at least one ECM G_k is not proportional to the identity matrix , said method comprising calculating a respective Channel Quality Indicator (CQI) q_k for at least one of said K transmission channels, and scheduling at least one of said K transmission channels for the transmission of said matrix modulated data symbols, wherein said scheduling is at least partially based on said calculated CQIs q_k.

Said transmission channel k may for instance describe the physical propagation channel between a single- or multi-antenna transmitter and a single- or multi-antenna receiver. There may be only one or several transmitters, and, correspondingly, there may be one or several receivers. Said transmitters and receivers may represent base stations, mobile stations or relay stations of a wireless communication system. A transmission channel k may be defined for both the up- and downlink. A transmission channel k may further relate to a channel between only a sub-group of transmit antenna elements of a multi-antenna transmitter and a single- or multi-antenna receiver, or to a channel between a single or multi-antenna transmitter and a sub-group of antenna elements of a receiver.

Data symbols, which may for instance represent BPSK, QPSK or QAM modulation symbols, are matrix modulated and transmitted via said respective transmit interfaces of said transmission channel k. Said matrix modulation represents a mapping of data symbols onto non-orthogonal spatial resources and (substantially) orthogonal

resources, as for instance time slots, frequency
carriers, orthogonal codes, spatial or polarisation
eigenmodes, or combination of these etc. Said matrix
modulation may be defined by a modulation matrix, that is
a linear function of said data symbols that are to be
transmitted via the $N_{t,k}$ transmission interfaces of said
transmission channel k. For space-time matrix modulation,
said modulation matrix may define when data symbols
and/or functions of said data symbols are transmitted
from which transmit interface in which symbol period. The
space-time matrix modulation then can be understood as a
mapping of data symbols and functions thereof to N_t
respective data streams that are transmitted by N_t
respective transmit interfaces during T symbol periods.
Similarly, in space-frequency matrix modulation, the
modulation matrix defines which symbols are transmitted
from which transmit interface with which frequency.
Instead of time and frequency, further orthogonal or
substantially orthogonal domains may be used, for
instance the code domain, polarization domain, eigenmode
domain, etc.

Said transmission of said matrix modulated data symbols
over one of said transmission channels $k=1,..,K$ may be
defined by a transmission channel matrix which contains
one respective entry to characterise the attenuation and
phase shift the data symbols undergo when being
transmitted on a respective channel between a transmit
interface and a receive interface. Said transmission
channel may be a wired or wireless transmission channel.

The effects of said modulation matrix and said
transmission channel matrix are combined in said
equivalent channel matrix G_k, which then describes the

matrix modulation of data symbols and the transmission
and reception of said matrix modulated data symbols using
the transmission channel k between the transmission
interfaces and the reception interfaces. Said
transmission interfaces of said transmission channel may
be connected to one or several transmitters, and,
correspondingly, the reception interfaces of said
transmission channel may be connected to one or more
receivers.

The ECCM R_k of said equivalent channel is not proportional
to the identity matrix, so that the matrix modulation
scheme is classified as non-orthonormal matrix modulation
scheme. Thus when a matched filter is applied at the
receiver side of the transmission channel k, the matched
filter estimate of the data symbols suffers from self-
interference between the data symbols. A non-orthonormal
matrix modulation scheme may for instance be constructed
by the linear combination of orthonormal matrix
modulation techniques such as space-time codes, space-
frequency codes or the like.

Scheduling is performed by a scheduling instance at
either the transmission side or the reception side of
said transmission channel to decide which of the K
transmission channels are best suited to be used for
transmitting data symbols that are matrix modulated by
and subsequently transmitted to the receiver side of the
said transmission channel.

Scheduling is at least partially based on CQIs q_k that
have been computed for at least one of said K respective
transmission channels. In may be preferred that CQIs q_k
are computed for at least two of said K respective
transmission channels. Then scheduling may be determined

by comparison of said CQIs which transmission channel is
more suited for transmission of data symbols. Scheduling
may also be performed in a way that once the CQI for some
transmission channel is above a set limit then that
transmission channel is used - therefore in some cases in
may be enough to calculate only one CQI.

CQIs may not have to be calculated for all the K
transmission channels between which the selection is
made: prior knowledge on CQIs of transmission channels or
some other means to avoid repeated calculation may be
applied also.

The K transmission channels to be selected from may not
all use the same modulation, for example some of them may
use orthonormal matrix modulations, and others may use
non-orthonormal matrix modulation, vector modulation,
single antenna transmission or diversity transmission.
Correspondingly, the CQIs for the respective transmission
channels may be computed in different fashions depending
on the modulation technique that is applied for the data
symbols that are to be transmitted via said respective
transmission channel.

At least one ECM G_k can be defined to describe the non-
orthonormal matrix modulation of said data symbols and
their transmission over a specific transmission channel,
which may be entirely defined by a channel matrix H_k. The
ECCM R_k of said ECM G_k then is not proportional to the
identity matrix, due to the fact that the matrix
modulation is non-orthonormal. Said ECCM can then be
either a non-diagonal matrix, or a diagonal matrix with
unequal entries on the diagonal. The non-diagonality
reflects the fact that interference arises between the

matrix modulated data symbols that can not simply be
removed by matched filtering at the receiving side of the
specific transmission channel. If matrix modulation is
performed for more than one of the K transmission
channels, more than one ECM G_k with a respective ECCM R_k
can be defined. However, only the ECCMs R_k of the
transmission channels on which non-orthonormal matrix
modulation is performed will not be proportional to the
identity matrix, whereas the ECCMs of transmission
channels that use orthonormal matrix modulation will be
proportional to the identity matrix.

Depending on the definition of the transmission channels,
scheduling may be applied to select between multiple
users in the uplink or downlink of a wireless
communication system, or to select between multiple
groups of Tx antennas, where matrix modulation is used on
the selected subgroup of antennas. Furthermore, if a
receiver may be equipped with less RF-circuitry than
antenna elements, the receiver may select the best
antenna/antennas to receive a transmission with. If the
transmitter uses matrix modulation, each possible choice
of receive antennas at the receiver is interpreted as a
transmission channel according to this invention. The
receiver then may choose the (set of) receive antenna(s)
based on CQIs disclosed in this invention.

Scheduling may be performed in the time, frequency or
code dimension or any combination of these, for example
the matrix modulation can be performed in frequency, but
the scheduling in both time and freq. For instance, based
on said at least one calculated CQI, a scheduler may
determine which transmission channel is scheduled for the
next time slot, or which transmission channel is

scheduled for a sub-carrier, polarization, spatial
eigenmode, etc.

Scheduling may be further applied in a handover situation
to select between multiple base stations in uplink or
downlink transmission. In the downlink, this may require
cooperation between multiple base stations.

One or more transmission channels may be scheduled for
transmissions of matrix modulated data symbols,
simultaneously. On the receiving side of the transmission
channel, a receiver may be equipped with one or more
receive interfaces and apply receive diversity combining
techniques.

Thus in contrast to the prior art approach of performing
scheduling in combination with orthonormal matrix
modulation in a selection diversity setting, which, for
increasing numbers of transmission channels proves to be
of inferior performance than scheduling without transmit
diversity, according to the present invention, scheduling
is performed in combination with non-orthonormal matrix
modulation in a selection diversity setting. The non-
orthonormal matrix modulation scheme can be considered to
introduce additional diversity into the equivalent
channels between and thus proves to be superior to both
the orthonormal matrix modulation approach and the
approach without transmit diversity.

According to the method of the present invention, it may
be preferred that said respective CQI q_k is derived for at
least one of said K transmission channels from said ECCM
R_k.

The at least one ECCM R_k corresponding to the at least one
ECM G_k contains both the effects of matrix modulation and
the transmission channel and is thus especially suited as
a basis for scheduling. The equivalent channel matrices G_k
are advantageously known by the scheduler when scheduling
is performed.

According to the method of the present invention, it is
preferred that said respective CQI q_k is calculated for at
least one of said K transmission channels as a function
of the determinant of a linear function of said ECCM R_k.

The determinant of the ECCM R_k has a strong correlation
with the BER that is achieved when data symbols are
matrix modulated and transmitted via a transmission
channel k as prescribed by the equivalent channel matrix
G_k. Said strong correlation to the BER causes the
scheduling to be based on the expected error rate of the
transmission and thus allows scheduling to reduce the
average error rate in a wireless communication system.
The correlation may be even further enhanced by
considering the determinant of a constant times the
identity matrix plus the ECCM R_k, i.e. $\det(aI + R_k)$, and
adjusting the constant a according to the used
transmission and detection scheme. The constant a may
also be chosen equal to zero. Said function of said
determinant may for instance be a power or a root of said
determinant, or a multiple thereof, or further
mathematical functions.

According to the method of the present invention, it may
also be preferred that said respective CQI q_k is
calculated for at least one of said K transmission
channels as a function of the trace of said ECCM R_k.

The trace of said ECCM also exhibits a strong correlation with the BER that is achieved when data symbols are matrix modulated and transmitted via a transmission channel k as prescribed by the equivalent channel matrix G_k. Furthermore, the computational costs for calculating the trace of an unstructured ECCM R_k are comparatively low.

According to the method of the present invention, it may also be preferred that said respective CQI q_k is calculated for at least one of said K transmission channels as a function of the trace of the inverse of said ECCM R_k.

The trace of the inverse of said ECCM also exhibits a strong correlation with the BER that is achieved when data symbols are matrix modulated and transmitted via a transmission channel k as prescribed by the equivalent channel matrix G_k.

Alternatively, any combination of the above-mentioned calculation methods for the CQIs, for instance a function of the determinant, the trace or the trace of the inverse of the ECCM, or some other function of the ECCM, may be taken as the CQI. For example, the determinant of the matrix $\left(aI + \rho R_k\right)$ can be interpreted in this way, wherein I denotes the identity matrix and a is a constant. This may be expanded in the carrier-to-interference-and-noise power ratio ρ, and coefficients of this expansion are the trace of R_k, the determinant of R_k and other symmetric polynomials of R_k. The constant a may be adjusted according to the used transmission and reception scheme.

According to the method of the present invention, it is
preferred that said respective CQI q_k is calculated for at
least one of said K transmission channels as a function
of the elements of a channel matrix H_k, which defines said
at least one transmission channel, and wherein said
function is derived from said ECCM R_k under exploitation
of the structural properties of said ECCM R_k.

Said channel matrix H_k defines the physical propagation
channel between the respective transmission interfaces
and the respective reception interfaces of said at least
one transmission channel. Preferably said channel matrix
H_k defines the transmission channel for which said at
least one ECM G_k can be defined. Said equivalent channel
matrix G_k then represents the combination of a modulation
matrix and said channel matrix H_k. Due to the structure of
the modulation matrix, which is inherited by said
equivalent channel matrix G_k, also the ECCM R_k possesses a
structure that can be exploited to save computations when
calculating the determinant or trace or other functions
of the ECCM R_k. In particular, closed-form expressions for
the CQIs q_k can be derived that may only depend on single
elements of the channel matrix H_k. Instead of having to
compute the ECCM R_k itself and then to calculate the CQI
q_k from said ECCM R_k when calculating the CQI q_k for a
transmission channel k during scheduling, only said
computationally efficient closed-form expression in the
elements of the channel matrix H_k has to be calculated.
For preferred embodiments, providing said simple closed-
form expressions significantly reduces the complexity of
calculating the CQI q_k for matrix modulators down to the
$2Q$-th root, where Q is the number of data symbols in the
matrix modulator.

The structure of the ECCM R_k may equally well be exploited
at the receiving side of the transmission channel when
estimating the received matrix modulated data symbols by
means of equalisation or multi-user detection. In
particular, computation of the determinant or the inverse
of the ECCM R_k is vastly simplified by exploiting its
structure.

It is understood that, if all of the K transmission
channels $k=1,..,K$ are suited for the transmission of non-
orthonormally matrix modulated data symbols, each of said
transmission channels k may be characterized by a
respective channel matrix H_k, respective ECM G_k and
respective ECCM R_k, and the respective CQI q_k may then be
calculated for each of these K transmission channels from
the respective R_k or H_k. Scheduling then may be based on
the comparison of all of these respective CQIs q_k.

According to a first embodiment of the present invention,
said non-orthonormal matrix modulation is so-called
"ABBA" non-orthonormal matrix modulation that maps a
block of 4 data symbols onto $N_{t,k}=4$ transmission
interfaces in 4 units of said at least one orthogonal
domain and is based on the non-orthonormal combination of
two Space-time Transmit Diversity (STTD) codes. Said
units of said at least one orthogonal domain may for
instance be time slots or frequency sub-carriers, so that
said non-orthonormal matrix modulation then becomes a
space-time or space-frequency matrix modulation,
respectively. An example of an orthonormal STTD code is
given by the transpose of the Alamouti code in equation
(1).

According to said first preferred embodiment of the
present invention, said ECCM R_k is of the form

$$R_k = \begin{bmatrix} p_k & 0 & n_k & 0 \\ 0 & p_k & 0 & n_k \\ n_k & 0 & p_k & 0 \\ 0 & n_k & 0 & p_k \end{bmatrix}, \text{ and}$$

p_k and n_k are real-valued functions of the elements of
said channel matrix H_k.

This structure of the ECCM R_k is for instance encountered
in the so-called "ABBA" non-orthonormal matrix modulation
scheme. If being applied as space-time matrix modulation,
the corresponding modulation matrix contains two STTD
blocks X_A and X_B (cf. the transpose of equation (1)) that
modulate 4 data symbols onto 4 transmit interfaces during
4 symbol periods, so that in effect 1 symbol is
transmitted per symbol period (so-called symbol rate 1
matrix modulation).

According to said first preferred embodiment of the
present invention, said respective CQI q_k is preferably
calculated for at least one of said K transmission
channels as a function of $\left((a+p_k)^2 - n_k^2\right)$, and wherein a is
a constant value. Said respective CQI q_k thus is
efficiently computed from the real-valued functions p_k and
n_k that only depend on the elements of said channel matrix
H_k. The constant a may be adjusted according to the used
transmission and reception scheme.

According to a second preferred embodiment of the present
invention, said non-orthonormal matrix modulation is a
DABBA non-orthonormal matrix modulation that maps a block
of 8 data symbols onto $N_{t,k}=4$ transmission interfaces in 4

units of said at least one orthogonal domain and is based
on the non-orthonormal combination of four STTD codes.
Said units of said at least one orthogonal domain may for
instance be time slots or frequency sub-carriers, so that
said non-orthonormal matrix modulation then becomes a
space-time or space-frequency matrix modulation,
respectively. An example of an orthonormal STTD code is
given by the transpose of the Alamouti code in equation
(1).

According to said second preferred embodiment of the
present invention, said ECCM R_k is of the form

$$R_k = \begin{bmatrix} p_{k,1}+p_{k,2} & 0 & n_{k,1} & 0 & p_{k,1}-p_{k,2} & 0 & i\cdot n_{k,2} & s_k^* \\ 0 & p_{k,1}+p_{k,2} & 0 & n_{k,1} & 0 & p_{k,1}-p_{k,2} & -s_k & i\cdot n_{k,2} \\ n_{k,1} & 0 & p_{k,1}+p_{k,2} & 0 & i\cdot n_{k,2} & -s_k^* & -p_{k,1}+p_{k,2} & 0 \\ 0 & n_{k,1} & 0 & p_{k,1}+p_{k,2} & s_k & i\cdot n_{k,2} & 0 & -p_{k,1}+p_{k,2} \\ p_{k,1}-p_{k,2} & 0 & i\cdot n_{k,2} & s_k^* & p_{k,1}+p_{k,2} & 0 & n_{k,1} & 0 \\ 0 & p_{k,1}-p_{k,2} & -s_k & i\cdot n_{k,2} & 0 & p_{k,1}+p_{k,2} & 0 & n_{k,1} \\ i\cdot n_{k,2} & -s_k^* & -p_{k,1}+p_{k,2} & 0 & n_{k,1} & 0 & p_{k,1}+p_{k,2} & 0 \\ s & i\cdot n_{k,2} & 0 & -p_{k,1}+p_{k,2} & 0 & n_{k,1} & 0 & p_{k,1}+p_{k,2} \end{bmatrix}$$

wherein $p_{k,1}$, $p_{k,2}$, $n_{k,1}$ and $n_{k,2}$ are real-valued functions
of the elements of said channel matrix H_k and wherein s_k
is a complex-valued function of the elements of said
channel matrix H_k. This structure of the ECCM R_k is for
instance encountered in the so-called "DABBA" non-
orthonormal matrix modulation scheme. If being applied as
space-time matrix modulation scheme, the corresponding
modulation matrix comprises linear combinations of 4 STTD
blocks X_A, X_B, X_C and X_D and modulates 8 data symbols onto
4 transmit interfaces during 4 symbol periods, so that in
effect 2 symbols are transmitted per symbol period (so-
called symbol rate 2 matrix modulation).

According to said second preferred embodiment of the
present invention, said respective CQI q_k is preferably
calculated for at least one of said K transmission
channels as a function of

$$\left(4 \cdot p_{k,1} \cdot p_{k,2} + (p_{k,1} + p_{k,2})(a^2 + 2 \cdot a) + n_{k,1}^2 - n_{k,2}^2 + |s_k|^2\right)^4,$$ and wherein a
is a constant value. Said respective CQI q_k thus is
efficiently computed from the real-valued functions $p_{k,1}$,
$p_{k,2}$, $n_{k,1}$ and $n_{k,2}$ and the complex valued function s_k that
only depend on the elements of said channel matrix H_k. The
constant a may be adjusted according to the used
transmission and reception scheme.

According to a third preferred embodiment of the present
invention, said non-orthonormal matrix modulation is a
TSTTD non-orthonormal matrix modulation that maps a block
of 4 data symbols onto $N_{t,k}=2$ transmission interfaces in 2
units of said at least one orthogonal domain and is based
on the non-orthonormal combination of two STTD codes.

Said units of said at least one orthogonal domain may for
instance be time slots or frequency sub-carriers, so that
said non-orthonormal matrix modulation then becomes a
space-time or space-frequency matrix modulation,
respectively. An example of an orthonormal STTD code is
given by the transpose of the Alamouti code in equation
(1).

According to said third preferred embodiment of the
present invention, said ECCM R_k is of the form

$$R_k = \begin{bmatrix} p_{k,1} + p_{k,2} & 0 & p_{k,1} - p_{k,2} & s_k \\ 0 & p_{k,1} + p_{k,2} & s_k^* & p_{k,2} - p_{k,1} \\ p_{k,1} - p_{k,2} & s_k & p_{k,1} + p_{k,2} & 0 \\ s_k^* & p_{k,2} - p_{k,1} & 0 & p_{k,1} + p_{k,2} \end{bmatrix},$$

wherein $p_{k,1}$ and $p_{k,2}$ are real-valued functions of the elements of said channel matrix H_k and wherein s_k is a complex-valued function of the elements of said channel matrix H_k. This structure of the ECCM R_k is for instance encountered in the so-called "Twisted or Twice STTD (TSTTD)" non-orthonormal matrix modulation scheme. If being applied as a space-time matrix modulation, the corresponding modulation matrix is represented by the sum of a STTD block X_A and a STTD block X_B (cf. the transpose of equation (1)) that modulates 4 data symbols onto 2 transmit interfaces during 2 symbol periods, so that in effect 2 symbols are transmitted per symbol period (so-called rate 2 matrix modulation).

According to the third preferred embodiment of the present invention, said respective CQI q_k is preferably calculated for at least one of said K transmission channels as a function of $\left(\det \left(aI + H_k^H H_k \right) \right)$, and wherein a is a constant value. The respective CQI q_k thus can be directly determined from the transmission channel matrix H_k without requiring the actual computation of the ECCM R_k. The constant a may be adjusted according to the used transmission and reception scheme.

According to the method of the present invention, it may be preferred that said non-orthonormal matrix modulation is a DSTTD non-orthonormal matrix modulation that maps a block of 4 data symbols onto $N_{t,k}=4$ transmission interfaces in 2 units of said at least one orthogonal

domain and is based on the non-orthonormal combination of
two STTD codes.

Said units of said at least one orthogonal domain may for
instance be time slots or frequency sub-carriers, so that
said non-orthonormal matrix modulation then becomes a
space-time or space-frequency matrix modulation,
respectively. An example of an orthonormal STTD code is
given by the transpose of the Alamouti code in equation
(1).

According to the method of the present invention, it is
preferred that said non-orthonormal matrix modulation
comprises space-time or space-frequency coding. The
modulation matrix of said matrix modulation may for
instance represent a linear combination of STTD blocks,
or may contain STTD blocks or linear combinations or
functions thereof as sub-matrices.

According to the method of the present invention, it is
preferred that said non-orthonormal matrix modulation
comprises a combination of at least two orthonormal
matrix modulations. For instance, a modulation matrix
that defines said matrix modulation may be the sum of two
orthonormal STTD blocks, so that a rate 2 non-orthonormal
matrix modulation is obtained instead of a rate 1
orthonormal matrix modulation as represented by a STTD
block.

It is further proposed a method for scheduling at least
one out of K transmission channels $k=1,..,K$ with
respective $N_{t,k}$ transmission interfaces and respective $N_{r,k}$
reception interfaces for the transmission of data
symbols, wherein at least two of said data symbols are

transmitted in parallel from $N_{t,k}$ transmission interfaces
of at least one of said K transmission channels, which is
defined by a channel matrix H_k, said method comprising
calculating a respective Channel Quality Indicator (CQI)
q_k for at least one of said K transmission channels,
wherein at least one of said respective CQIs q_k is
calculated as a function of the determinant of a a linear
function of the channel correlation matrix $H_k^H \cdot H_k$ of said
channel matrix H_k, and
scheduling at least one of said K transmission channels
for the transmission of said data symbols, wherein said
scheduling is at least partially based on said calculated
CQIs q_k.

At least two of said data symbols are transmitted from
said respective $N_{t,k}$ transmission interfaces in parallel,
for instance one data symbol may be transmitted from a
first transmission interface and a second data symbol
from a second transmission interface. If said
transmission interfaces are the antenna elements of a
transmitter, said two data symbols cause interference to
each other when being received at the reception
interfaces of a transmission channel k. Transmitting said
at least two data symbols in parallel may be considered
as a vector modulation scheme, wherein data symbols are
mapped to a non-orthogonal spatial resource. A
representative of such as vector modulation scheme is the
Bell Laboratories Layered Space Time Architecture
(BLAST). In contrast to matrix modulation schemes,
diversity is only used in the spatial domain without
exploiting orthogonal domains as for instance the time,
frequency or polarization domain.

The determinant of said matrix $aI + H_k^H H_k$ or other functions thereof exhibits a strong correlation with the BER that is achieved when data symbols are transmitted from a transmitter using the transmission channel k as prescribed by the channel matrix H_k.

With respect to the interpretation of the transmission channels and the scheduling scenarios, the above description of the types of transmission channels and scheduling scenarios for the matrix modulation applies for the vector modulation as well.

According to the method of the present invention, it is preferred that at least one receiver uses a Maximum Likelihood algorithm or a linear estimator to estimate said data symbols that are transmitted over said scheduled transmission channel and received by said receiver via said reception interfaces of said scheduled transmission channel.

Due to the use of a non-orthonormal matrix or vector modulation scheme, an estimate for the data symbols that is based on matched filtering of the matrix/vector modulated, transmitted and received data symbols may contain self-interference to a degree that renders the correct estimation of the data symbols impossible. It is then advantageous to perform maximum likelihood or reduced complexity linear equalisation techniques such as for instance a zero-forcing algorithm or a minimum mean-square error algorithm. Both approaches may advantageously be based on a sufficient set of statistics that is obtained by matched filtering of the data symbols received via the reception interfaces of said transmission channel.

According to the method of the present invention, it may
be preferred that a transmission channel $k=1,..,K$ with
the largest CQI q_k is scheduled for said transmission of
said data symbols.

In particular if all K transmission channels employ the
same matrix modulation, it is preferred that the
transmission channel $k=1,..,K$ with the largest CQI q_k is
scheduled. The BER is approximated closely by a strictly
monotonic decreasing function of the determinant of a
linear function of the ECCM R_k and the trace of the ECCM
R_k. The lowest BER, or lowest power consumption when the
target BER is fixed, thus is achieved when transmitting
data via the transmission channel with the largest CQI q_k.
Alternatively one may want to minimize the used
transmission power for an expected error probability.
This is performed in a similar way using the same CQI q_k.

If different transmission channels employ different
matrix modulations, possibly with different rates, the
calculated $CQIe_k$, characterizing the error probabilities
of the transmission channels, together with the rates and
modulation types characterized by $CQIm_k$, are used to
select the transmission channel that provides the highest
rate with a given power and expected error probability,
or the transmission channel with provides the lowest
error probability with an expected rate and given power,
or the transmission channel that uses the least power to
reach an expected error probability with an expected
rate. To achieve this, the error probabilities for each
transmission mode can be approximated for example in a
log-log scale as linear functions of the $CQIe_k$, with
suitable parameters to give the best fit. The approximate

functions are quite accurate and can be used to find solutions to the minimization problems.

According to the method of the present invention, it may be preferred that said transmission channels are transmission channels of a wireless communication system, and that said transmission and reception interfaces of said transmission channels are the transmit and receive antenna elements of one or several transmitters and one or several receivers, respectively.

Said wireless communication system may for instance be the Universal Mobile Telecommunications System (UMTS), the Global System for Mobile Communications (GSM), or a system according to the Interim Standard 95 (IS-95). Alternatively, it may be a Wireless Local Area Network (W-LAN) system like the HIPERLAN/2 or 802.11 system.

It is further proposed a computer program with instructions operable to cause a processor to perform the above-mentioned method steps.

It is further proposed a computer program product comprising a computer program with instructions operable to cause a processor to perform the above-mentioned method steps.

It is further proposed a device for scheduling at least one out of K transmission channels $k=1,..,K$ with respective $N_{t,k}$ transmission interfaces and respective $N_{r,k}$ reception interfaces for the transmission of data symbols modulated according to a non-orthonormal matrix modulation that modulates data symbols in both a non-orthogonal spatial domain and at least one orthogonal

domain, wherein at least one Equivalent Channel Matrix
(ECM) G_k can be defined that transforms said data symbols
into data symbols that have been matrix modulated,
transmitted over $N_{t,k}$ transmission interfaces and received
at $N_{r,k}$ reception interfaces of one of said transmission
channels $k=1,..,K$, and wherein an Equivalent Channel
Correlation Matrix (ECCM) $R_k = G_k^H \cdot G_k$ of said at least one
ECM G_k is not proportional to the identity matrix, said
device comprising means for calculating a respective
Channel Quality Indicator (CQI) q_k for at least one of
said K transmission channels, and
means for scheduling at least one of said K transmission
channels for the transmission of said matrix modulated
data symbols, wherein said scheduling is at least
partially based on said calculated CQIs q_k.

It is further proposed a transmitting station in a
wireless communication system that schedules at least one
out of K transmission channels $k=1,..,K$ with respective
$N_{t,k}$ transmission interfaces and respective $N_{r,k}$ reception
interfaces for the transmission of data symbols modulated
according to a non-orthonormal matrix modulation that
modulates data symbols in both a non-orthogonal spatial
domain and at least one orthogonal domain, wherein at
least one Equivalent Channel Matrix (ECM) G_k can be
defined that transforms said data symbols into data
symbols that have been matrix modulated, transmitted over
$N_{t,k}$ transmission interfaces and received at $N_{r,k}$ reception
interfaces of one of said transmission channels
$k=1,..,K$, and wherein an Equivalent Channel Correlation
Matrix (ECCM) $R_k = G_k^H \cdot G_k$ of said at least one ECM G_k is
not proportional to the identity matrix, said
transmitting station comprising

means for calculating a respective Channel Quality
Indicator (CQI) q_k for at least one of said K transmission
channels, and means for scheduling at least one of said K
transmission channels for the transmission of said matrix
modulated data symbols, wherein said scheduling is at
least partially based on said calculated CQIs q_k.

It is further proposed a wireless communication system,
comprising at least one transmitting station, and at
least one receiving station, wherein a non-orthonormal
matrix modulation modulates data symbols in both a non-
orthogonal spatial domain and at least one orthogonal
domain, wherein said matrix modulated data symbols are
transmitted over at least one out of K transmission
channels $k=1,..,K$ with respective $N_{t,k}$ transmission
interfaces and respective $N_{r,k}$ reception interfaces,
wherein at least one Equivalent Channel Matrix (ECM) G_k
can be defined that transforms said data symbols into
data symbols that have been matrix modulated, transmitted
over $N_{t,k}$ transmission interfaces and received at $N_{r,k}$
reception interfaces of one of said transmission channels
$k=1,..,K$, wherein an Equivalent Channel Correlation
Matrix (ECCM) $R_k = G_k^H \cdot G_k$ of said at least one ECM G_k is
not proportional to the identity matrix, wherein said at
least one transmitting station calculates a respective
Channel Quality Indicator (CQI) q_k for at least one of
said K transmission channels, and schedules at least one
of said K transmission channels for the transmission of
said matrix modulated data symbols, wherein said
scheduling is at least partially based on said calculated
CQIs q_k.

It is further proposed a device for scheduling at least
one out of K transmission channels $k=1,..,K$ with

respective $N_{t,k}$ transmission interfaces and respective $N_{r,k}$
reception interfaces for the transmission of data
symbols, wherein at least two of said data symbols are
transmitted in parallel from $N_{t,k}$ transmission interfaces
of at least one of said K transmission channels, which is
defined by a channel matrix H_k, said device comprising
means for calculating a respective Channel Quality
Indicator (CQI) q_k for at least one of said K transmission
channels, wherein at least one of said respective CQIs q_k
is calculated as a function of the determinant of a
linear function of a channel correlation matrix $H_k^H \cdot H_k$ of
said channel matrix H_k, and means for scheduling at least
one of said K transmission channels for the transmission
of said data symbols, wherein said scheduling is at least
partially based on said calculated CQIs q_k.

It is further proposed a transmitting station that
schedules at least one out of K transmission channels
$k=1,..,K$ with respective $N_{t,k}$ transmission interfaces and
respective $N_{r,k}$ reception interfaces for the transmission
of data symbols, wherein at least two of said data
symbols are transmitted in parallel from $N_{t,k}$ transmission
interfaces of at least one of said K transmission
channels, which is defined by a channel matrix H_k,
said transmitting station comprising means for
calculating a respective Channel Quality Indicator (CQI)
q_k for at least one of said K transmission channels,
wherein at least one of said respective CQIs q_k is
calculated as a function of the determinant of a linear
function of a channel correlation matrix $H_k^H \cdot H_k$ of said
channel matrix H_k, and means for scheduling at least one
of said K transmission channels for the transmission of

said data symbols, wherein said scheduling is at least
partially based on said calculated CQIs q_k.

It is further proposed a wireless communication system,
comprising at least one transmitting station, and
at least one receiving station, wherein at least two data
symbols are transmitted in parallel from $N_{t,k}$ transmission
interfaces of at least one out of K transmission channels
with $N_{t,k}$ transmission interfaces and $N_{r,k}$ reception
interfaces, wherein said at least one transmission
channel is defined by a channel matrix H_k, wherein said
transmitting station calculates a respective Channel
Quality Indicator (CQI) q_k for at least one of said K
transmission channels, wherein said transmitting station
calculates at least one of said respective CQIs q_k is as a
function of the determinant of a linear function of a
channel correlation matrix $H_k^H \cdot H_k$ of said channel matrix
H_k, wherein said at least one transmitting station
schedules at least one of said K transmission channels
for the transmission of said data symbols, and wherein
said scheduling is at least partially based on said
calculated CQIs q_k.

These and other aspects of the invention will be apparent
from and elucidated with reference to the embodiments
described hereinafter.

Brief description of the figures
In the figures show:

Fig. 1:   the Bit Error Ratio (BER) performance
               achieved when scheduling different numbers
               of transmission channels K in combination
               with an orthonormal matrix modulation

scheme with two transmit antenna elements
(Space Time Transmit Diversity, STTD,
dashed lines) and in combination with a
single antenna transmission without STTD
(solid lines) according to the prior art;

Fig. 2:   the Probability Density Function (PDF) of
the Signal-to-Noise Ratio (SNR) for the
scheduled transmission channel when
scheduling of different numbers of
transmission channels K is performed in
combination with an orthonormal matrix
modulation scheme with two transmit antenna
elements (Space Time Transmit Diversity,
STTD, dashed lines) and in combination with
a single antenna transmission without STTD
(solid lines) according to the prior art;

Fig. 3:   a table indicating the reduction of the
computational complexity required to
calculate R_k and det R_k for different non-
orthonormal matrix modulation schemes
according to the present invention;

Fig. 4:   the correlation between the BER and the
CQI $q_k=$det R_k for different orthonormal and
non-orthonormal matrix modulation schemes
according to the present invention;

Fig. 5A: the BER as a function of E_b/N_0 for
different orthonormal (STTD) and non-
orthonormal (TSTTD) matrix modulation
schemes and different choices of CQI when
scheduling one out of $K=2$ transmission

channels according to the present
invention;

Fig. 5B: the BER as a function of E_b/N_0 for
                  different non-orthonormal (ABBA, DSTTD)
                  matrix modulation schemes and different
                  choices of CQI when scheduling one out of
                  $K=2$ transmission channels according to the
                  present invention;

Fig. 5C: the BER as a function of E_b/N_0 for
                  the non-orthonormal DABBA matrix modulation
                  scheme and different choices of CQI when
                  scheduling one out of $K=2$ transmission
                  channels according to the present
                  invention;

Fig. 6:   the BER as a function of E_b/N_0 for
                  scheduling in combination with non-
                  orthonormal BLAST and TSTTD matrix
                  modulations for different numbers of
                  transmission channels K according to the
                  present invention;

Fig. 7:   a flowchart of a method according to the
                  present invention; and

Fig. 8:   a device according to the present
                  invention.

Detailed description of the invention
The present invention proposes to combine non-orthonormal
matrix modulation with scheduling in a selection

diversity setting. This approach may depend on the definition of the Channel Quality Indicator (CQI) that serves as a basis for the decision which of the K transmission channels are scheduled to be used for transmitting data symbols that are matrix modulated and transmitted by a transmitter.

The need for the definition of CQI's generally arises in situations where the transmission schemes need to be adapted according to the channel conditions, and different types of adaptation methods require different CQIs. Two distinct types of adaptation can be identified:

1. In systems with multiple transmission channels as basis for resource allocation, for example scheduling methods in TDMA systems which allocate time slots to the transmission channel with the "best" channel. Here the $CQIe_k$ should correlate with the performance the channel can support.

2. Choosing the right coding and modulation mode to maximize the rate or throughput for the single transmission channel, depending on the channel conditions. The decision can be based on some $CQIm_k$ threshold values after which the coding/modulation should be changed. This means comparing the performance of two different codes/modulations for one fixed channel, so $CQIm_k$ should be sensitive to the number of data streams the channel can support.

Optimally, a CQI for selection diversity is given by the bit error rate, preferably after decoding of channel codes, or the corresponding frame error rate (FER). Often a CQI based on BER after demodulation is used. An ideal

CQI has a one-to-one correspondence to the bit error
rates (BER), or frame or block error rate. In single
stream (and orthogonal multi-stream) channels the CQI
with the best correlation to the BER/FER is the received
Signal-to-Noise Ratio (SNR), which for orthonormal
transmissions generalises to maximum ratio combined (MRC)
channel power. This is the generic maximum C/I scheduler
discussed e.g. in the Kogiantis reference.

For non-orthonormal transmissions, especially for MIMO
transmissions with multiple data streams as considered by
the present invention, the situation is not as simple any
more. The total channel power, generalising the overall
SNR or C/I, is now proportional to the trace of the
channel correlation matrix $\operatorname{tr} H_k^H H_k$. MIMO channels with the
same $\operatorname{tr} H_k^H H_k$ might still lead to very different bit/frame
error rates, depending on the specifics of the
transmission channel and the chosen transmission scheme.

Finding a good CQI becomes even more complicated when
matrix modulation is used to encode the signals. Matrix
modulators are designed to offer more diversity into the
transmission, and to maximise the mutual information
between transmitted and received signals. As a result
they possess inherent symmetries restricting their
structure. Therefore, the channel quality indicator does
not depend solely on the transmission channel, but also
on the way the symbols are matrix modulated and detected.
This means that in principle different matrix modulation
and/or detection methods may require different channel
quality indicators.

According to the present invention, thus CQI's suitable
for use in multiple transmission channel resource

allocation (type 1 in above classification) for non-
orthonormal matrix modulated systems are proposed. In
particular, comparatively simple CQI's are proposed,
which for some transmission modes are – up to the
simulation accuracy – in one-to-one correspondence with
the BER/FER for reduced search maximum likelihood
detection performed at a receiver that receives the data
transmission via the scheduled transmission channel.

Before the results of Figs. 3-7 are discussed, the non-
orthonormal matrix modulation schemes according to the
preferred embodiments of the present invention will be
briefly defined with reference to the orthonormal
Alamouti Space-Time code of equation (1) or the transpose
thereof (the latter is then denoted as Space-Time
Transmit Diversity (STTD) modulation matrix), the signal
model of equation (2), the equivalent signal model of
equation (3) and the definition of the Equivalent Channel
Correlation Matrix (ECCM) R_k of equation (6).

Note that the following embodiments concentrate on space-
time matrix modulation techniques, but are also directly
applicable to other non-orthonormal matrix modulation
techniques such as space-frequency or space-polarization
matrix modulation techniques. Thus the scope of the
present invention is not to be understood to be limited
by the following embodiments.

The non-orthonormal ABBA matrix modulation scheme
The modulation matrix of this scheme reads as

$$X_{ABBA} = \begin{bmatrix} X_A & X_B \\ X_B & X_A \end{bmatrix},$$

wherein X_A is the STTD modulation matrix as transpose of
equation (1) with two data symbols x_1 and x_2, and X_B is
the STTD modulation matrix as transpose of equation (1)
with two further data symbols x_3 and x_4. For optimal
performance, these symbols may be chosen as linear
combinations and/or rotations of the comple modulated
symbols. This applies to all matrix modulations discussed
in this invention. The modulation matrix X_{ABBA} thus
represents a rate 1 matrix modulator which maps 4 data
symbols onto 4 transmit antenna elements in 4 symbol
periods. The ECCM of the ABBA modulation scheme can be
identified as

$$R_k = \begin{bmatrix} p_k & 0 & n_k & 0 \\ 0 & p_k & 0 & n_k \\ n_k & 0 & p_k & 0 \\ 0 & n_k & 0 & p_k \end{bmatrix},$$

wherein p_k is the total power of all channels and n_k
denotes the strength of the interference between the two
different STTD blocks X_A and X_B.

For the exemplary case of $N_t=4$ transmit antennas and $N_{k,r}=2$
receive antennas, the real-valued functions p_k and n_k are
defined as:

$$p_k = \operatorname{tr} H_k^H H_k = \tfrac{1}{4} \sum |h_{k,ij}|^2$$

$$n_k = \tfrac{1}{2} \left(\operatorname{Re}(h_{k,13} h_{k,11}^*) + \operatorname{Re}(h_{k,12} h_{k,14}^*) + \operatorname{Re}(h_{k,23} h_{k,21}^*) + \operatorname{Re}(h_{k,24} h_{k,22}^*) \right).$$

It can be seen that R_k has only two distinct eigenvalues
$p_k \pm n_k$. Note that the number of distinct eigenvalues does
not depend on the size of the original channel matrix,

only the explicit forms of the elements p_k, n_k do. Since
the determinant is given by the product of the
eigenvalues we get for ABBA:

$$\det R_k = \left(p_k^2 - n_k^2 \right)^2 ,$$

which is proportional to $|\text{diagonal part}|^2$ - $|\text{off-diagonal}$
$\text{part}|^2$ of R_k. Note that, by using the structure of the
matrix modulator, we have first simplified the
calculation of $R_k = H_k^H H_k$ for $N_{k,r}$=2 receive antennas from
128 complex multiplications and 112 complex additions
(128 Cx, 112 C+) to 12 complex multiplications and 10
real additions (12 Cx, 10 R+), and further reduced the
complexity of calculating $\det R_k$ from (40 Cx, 30 C+) to
(3 Rx, 1 R+). This is a significant complexity reduction
indeed. Further complexity reduction can be found if the
inverse of R_k is needed for scheduling or detection; the
inverse is trivially

$$R_k^{-1} = \frac{1}{p_k^2 - n_k^2} \begin{bmatrix} p_k & 0 & -n_k & 0 \\ 0 & p_k & 0 & -n_k \\ -n_k & 0 & p_k & 0 \\ 0 & -n_k & 0 & p_k \end{bmatrix}$$

Note in particular that the diagonal elements of the
inverse are proportional to the trace and inversely
proportional to the determinant.

Instead of the determinant of the ECCM we can use also
the more general CQI of a determinant of a linear
function of the ECCM. For ABBA this simplies to
$\left((a + p_k)^2 - n_k^2 \right)$, where a is a constant which can be determined
numerically to maximize the correlation to the

performance. For example, for QPSK modulation and reduced search maximum likelihood detection, with two receive antennas the best fit was found for $a = 0.15$.

A variant of the ABBA matrix modulation is so called diagonal ABBA. The modulation matrix is written as

$$X_{ABBA} = \begin{bmatrix} X_A + X_B & 0 \\ 0 & X_A - X_B \end{bmatrix}$$

Now the ECCM is diagonal, but not orthonormal. The determinant of the ECCM is the same as for ordinary ABBA.

The non-orthonormal DABBA matrix modulation scheme
The modulation matrix of this scheme reads as

$$X_{DABBA} = \begin{bmatrix} X_A + X_C & X_B + X_D \\ X_B - X_D & X_A - X_C \end{bmatrix},$$

wherein X_A, X_B, X_C and X_D are the STTD modulation matrix as transposes of equation (1) with two data symbols each, respectively. The modulation matrix X_{DABBA} thus represents a rate 2 matrix modulator which maps 8 data symbols onto 4 transmit antenna elements in 4 symbol periods. The ECCM of the DABBA modulation scheme can be identified as

$$R_k = \begin{bmatrix} p_{k,1}+p_{k,2} & 0 & n_{k,1} & 0 & p_{k,1}-p_{k,2} & 0 & i \cdot n_{k,2} & s_k^* \\ 0 & p_{k,1}+p_{k,2} & 0 & n_{k,1} & 0 & p_{k,1}-p_{k,2} & -s_k & i \cdot n_{k,2} \\ n_{k,1} & 0 & p_{k,1}+p_{k,2} & 0 & i \cdot n_{k,2} & -s_k^* & -p_{k,1}+p_{k,2} & 0 \\ 0 & n_{k,1} & 0 & p_{k,1}+p_{k,2} & s_k & i \cdot n_{k,2} & 0 & -p_{k,1}+p_{k,2} \\ p_{k,1}-p_{k,2} & 0 & i \cdot n_{k,2} & s_k^* & p_{k,1}+p_{k,2} & 0 & n_{k,1} & 0 \\ 0 & p_{k,1}-p_{k,2} & -s_k & i \cdot n_{k,2} & 0 & p_{k,1}+p_{k,2} & 0 & n_{k,1} \\ i \cdot n_{k,2} & -s_k^* & -p_{k,1}+p_{k,2} & 0 & n_{k,1} & 0 & p_{k,1}+p_{k,2} & 0 \\ s & i \cdot n_{k,2} & 0 & -p_{k,1}+p_{k,2} & 0 & n_{k,1} & 0 & p_{k,1}+p_{k,2} \end{bmatrix}$$

where $p_{k,1}$, $p_{k,2}$ are the total channel powers from antenna
pairs (1, 2) and (3, 4) to all receive antennas,
respectively, $n_{k,1}$, $n_{k,2}$ are real combinations of the
elements of H_k, and s_k a complex term. Again, $p_{k,1}$ + $p_{k,2}$ on
the diagonal of R_k is the total channel power, and the
other terms on the off-diagonal describe the interference
between the blocks. And again, R_k has only two different
eigenvalues:

$$p_{k,1} + p_{k,2} \pm \sqrt{\left(p_{k,1} - p_{k,2}\right)^2 + n_{k,1}^2 - n_{k,2}^2 + \left|s_k\right|^2} \ ,$$

so the determinant reads as

$$\det R_k = \left(4 p_{k,1} p_{k,2} + n_{k,1}^2 - n_{k,2}^2 + \left|s_k\right|^2\right)^4 \ .$$

The inverse of R_k can be constructed in similar fashion as
for the ABBA scheme. The complexity reduction in this
case is really huge, and can be found in the table of
Fig. 3. Thus using the disclosed methods, scheduling of
high rate, high diversity modulators of the DABBA-kind
really becomes practical. Similar simple expression for
det R_k can be obtained to other matrix modulators as well,
due to their large internal symmetries.

For the det($a I$ + R_k),

$$\left(4 \cdot p_{k,1} \cdot p_{k,2} + (p_{k,1} + p_{k,2})(a^2 + 2a) + n_{k,1}^2 - n_{k,2}^2 + \left|s_k\right|^2\right)^4$$

The constant a can be again determined numerically, the
best value for QPSK modulation and reduced search maximum
likelihood detection, with two receive antennas was found
to be 0.04.

The non-orthonormal DSTTD matrix modulation scheme
The modulation matrix of this scheme reads as

$$X_{DSTTD} = \begin{bmatrix} X_A & X_B \end{bmatrix},$$

wherein X_A and X_B are the modulation matrix given by the transposed Alamouti code of equation (1) with two data symbols each, respectively. The modulation matrix X_{DSTTD} thus represents a rate 2 matrix modulator which maps 4 data symbols onto 4 transmit antenna elements in 2 symbol periods.

The non-orthonormal TSTTD matrix modulation scheme
The modulation matrix of this scheme reads as

$$X_{TSTTD} = X_A + \frac{1}{\sqrt{7}} \begin{bmatrix} 1+i & 1+2i \\ -1+2i & 1-i \end{bmatrix} \cdot X_B,$$

wherein X_A is the STTD modulation matrix as the transpose of equation (1) with two data symbols x_1 and x_2, and X_B is the STTD modulation matrix as the transpose of equation (1) with two further data symbols x_3 and x_4. The modulation matrix X_{TSTTD} thus represents a rate 2 matrix modulator which maps 4 data symbols onto 2 transmit antenna elements in 2 symbol periods. The ECCM of the TSTTD modulation scheme can be identified as

$$R_k = \begin{bmatrix} p_{k,1}+p_{k,2} & 0 & p_{k,1}-p_{k,2} & s_k \\ 0 & p_{k,1}+p_{k,2} & s_k^* & p_{k,2}-p_{k,1} \\ p_{k,1}-p_{k,2} & s_k & p_{k,1}+p_{k,2} & 0 \\ s_k^* & p_{k,2}-p_{k,1} & 0 & p_{k,1}+p_{k,2} \end{bmatrix}$$

where $p_{k,1}$ and $p_{k,2}$ are the total powers from transmit antennas 1 and 2 to all receive antennas, respectively, and s_k is given as

$$s_k = 2h_{k,11}^* h_{k,12} + 2h_{k,21}^* h_{k,22} ,$$

when H_k is 2×2. The ECCM R_k of TSTTD has the remarkable property that

$$\det R_k = \left(\det H_k^H H_k\right)^2 ,$$

indicating that in this case the equivalent-channel-based scheduling and matrix-channel-based scheduling are equivalent for the preferred CQI, leading to further simplification in calculating equivalent channel based CQIs.

Fig. 3 depicts the computational complexity encountered when calculating the ECCM R_k and its determinant det R_k for the ABBA, DABBA and TSTTD schemes directly, or with the simple closed-form expressions that are proposed by the present invention. The computational complexity is given in terms of real (RX) and complex (CX) multiplications and in terms of real (R+) and complex (C+) additions.

For the TSTTD scheme, det R_k can be calculated directly from det H_k. The complexity of the proposed algorithms for calculating the determinant is the $2Q$-th root of the complexity of the direct method, where Q is the number of complex symbols in the modulation, i.e. 4, 8 and 4 for ABBA, DABBA and TSTTD, respectively.

Fig. 4 depicts the correlation between the BER and the preferred CQI q_k=det R_k for different orthonormal (STTD) and non-orthonormal (ABBA, DSTTD, TSTTD and DABBA) matrix

modulation schemes according to the present invention.
The simulations assumed Additive White Gaussian Noise
(AWGN) at the receiving side of the transmission channel
with an E_b/N_0 fixed at 6 dB, QPSK modulated symbols were
used as data symbols, and the entries in the transmission
channel matrix were assumed to be i.i.d. Rayleigh-
distributed.

Apparently, the proposed CQI q_k=det R_k exhibits a strong
correlation to the BER for all simulated orthonormal and
non-orthonormal matrix modulation schemes. Because the
BER is a monotonic function of E_b/N_0, the qualitative
results obtained at one operation point should not change
with E_b/N_0. The results should persist also for higher
order modulations, since the pairwise error probabilities
can be expressed in terms of pairwise error probabilities
of a BPSK modulated system. The effects of other types of
detection instead of reduced search ML, such as for
instance linear detection algorithms as the zero-forcing
block linear detector or the minimum mean-square error
block linear detector is still to be studied.

Figs. 5A, 5B and 5C depict the simulated BER as a
function of E_b/N_0 for different orthonormal (STTD) and
non-orthonormal (TSTTD, ABBA, DSTTD and DABBA) matrix
modulation schemes and different choices of CQI when
scheduling one out of $K=2$ transmission channels according
to the present invention. Rayleigh-fading transmission
channels, AWGN at the reception interfaces of the
scheduled transmission channel, and opportunistic
scheduling of the transmission channel with the better
CQI irrespective of the state of the potential temporal
scheduling constraints such as mean packet delay, etc.
was performed. For STTD and TSTTD, 16-QAM modulated data

symbols were transmitted, whereas for ABBA, DSTTD and
DABBA, QPSK-modulated symbols were transmitted. Except
for STTD, which has a bit rate of 2 bps, all non-
orthonormal schemes have a bit rate of 4 bps.

For each matrix modulation scheme, the BER performance
without scheduling (one of the $K=2$ transmission channels
is chosen arbitrarily irrespective of his CQI), with CQI
q_k=det R_k and CQI q_k= det$H_k^H H_k$ is depicted. For the STTD,
DABBA and TSTTD schemes, additionally the BER performance
for CQI q_k=tr R_k is depicted.

As can be readily seen from Figs. 5A, 5B and 5C,
scheduling based on the CQI q_k=det R_k performs best for
all investigated matrix modulation schemes. However,
significant gains in E_b/N_0 with respect to the BER
performance of a system without scheduling are also
achieved for the CQIs based on the trace of R_k and the
determinant of $H_k^H H_k$.

Further possible choices of CQI comprise the trace of the
inverse of R_k, the condition number of H_k, the condition
number of G_k, and the ratio or difference between the
magnitude of the diagonal and off-diagonal parts of R_k.

The performance of vector modulation as for instance the
Bell Laboratories Layered Space Time Architecture (BLAST)
scheme in combination with scheduling in a selection
diversity setting with $K=2$ and $K=8$ transmission channels
is depicted in Fig. 6 and compared to the performance of
a TSTTD scheme.

In Fig. 6, both schemes use $N_t=2$ transmit and $N_{k,r}=2$
receive antenna elements and QPSK modulated data symbols,

the noise is AWGN, and the transmission channels are
i.i.d. flat Rayleigh-fading channels. In each scheme, 4
data symbols are transmitted during two time instants,
wherein the modulation matrix for the BLAST scheme reads
as

$$X_{BLAST} = \begin{bmatrix} x_1 & x_3 \\ x_2 & x_4 \end{bmatrix},$$

i.e. two data symbols are mapped to the non-orthogonal
spatial resources in each symbol period.

Fig. 6 depicts both the results for scheduling with $K=2$
and $K=8$ transmission channels and the results without any
scheduling. For the scheduling results, the transmission
channel with the maximum CQI $q_k = \det Rk$ was scheduled for
the TSTTD scheme, and the transmission channel with the
maximum CQI $q_k = \det H_k^H H_k$ was scheduled for the BLAST case.

It is clearly visible from Fig. 6 that scheduling
increases the performance of both TSTTD (dashed curves)
and BLAST (solid curves) in particular when the number of
transmission channels K is increased. The gains from the
scheduling are larger for the BLAST scheme so the
difference in its performance will decrease when more
transmission channels are added. But even for $K=8$
transmission channels the TSTTD still has better
performance at BER=10^{-3}, the difference in E_b/N_0 being
approximately 1.5 dB. Also, the simulation was for
opportunistic scheduling the results only show the upper
limit for the scheduling gains. In practice, the gains
may be smaller, which means that TSTTD may perform better
for even larger number of transmission channels

than expected from the opportunistic scheduling results.
Also, when the CQI is allowed to be proportional to the
determinant of a linear function, i.e. $q_k = \det(a\,I + H_k^H H_k)$
and the constant a is adjusted for each scheme to ensure
the best correlation between the CQI and BER it can be
seen that the gains will increase further. In this case
the optimal constant for TSTTD was 0.04, and for BLAST
0.0.

Fig. 7 depicts a flow chart according to the first
preferred embodiments of the present invention (the ABBA
non-orthonormal matrix modulation scheme).

In a first step 10, the transmission channel index is
initialised with 1, and a variable q_{max} is set to zero.
Subsequently the channel matrix H_k is fetched from a
storage or estimated from signals that have been received
via said transmission channel before. From said channel
matrix H_k, then the functions p_k and n_k are computed in a
step 12. In a step 13, the CQI $q_k = \det R_k$ is computed from
the functions p_k and n_k. This CQI q_k is then compared to
q_{max} in a step 14, and if q_k is larger than q_{max}, q_{max} is set
equal to q_k and a variable k_{max} is set equal to k in a step
15. In a step 16, the transmission channel index k is
increased by 1, and it is checked in a step 17 if the
transmission channel index k equals the number of
transmission channels K among which scheduling is
performed. If this is not the case, steps 11 to 16 are
repeated until the transmission channel index k equals K.
Then, in a step 18, matrix modulation according to the
ABBA scheme is performed for the data symbols that are to
be transmitted via the transmission channel with index
k_{max}. The matrix modulated data symbols then are

transmitted in a step 19, and the flowchart is processed
again starting with step 10.

Fig. 8 depicts a device according to the present
invention. The device comprises respective data packet
buffers 20-1 .. 20-3, which contain data packets that
arrive at said device and are to be transmitted via K
respective transmission channels, wherein in the example
of Fig. 8, $K=3$ holds. Each packet buffer 20-1 .. 20-3 is
controlled by a buffer controller 21-1..21-3,
respectively. The buffer controller 21-1..21-3 signals
the state of the buffers 20-1..20-3 to a scheduler 22.
Furthermore, when being triggered by said scheduler 22,
said buffer controllers 21-1..21-3 are capable of
transferring data packets to a matrix modulator 26,
wherein the data symbols contained in the data packets
are matrix modulated and subsequently transmitted via
transmit modules 27-1..27-4 and transmit antenna elements
28-1..28-4. Said scheduler 22 further receives input from
a CQI calculation instance 23, which fetches transmission
channel data from a channel storage 24, which in turn is
updated by a channel estimation instance 25. The CQI
calculation instance 23 determine CQIs for a number of K
transmission channels based on the respective
transmission channel data fetched from said channel
storage 24. For instance, when the ABBA matrix modulation
scheme is applied, said CQI calculation instance 23
computes the functions p_k and n_k from the entries $h_{k,ij}$ in
the channel matrices H_k and then determines a CQI q_k from
said functions p_k and n_k. The calculated CQIs are then fed
into the scheduler 22. Based on the input from the CQI
calculation instance 23 and on the input from the buffer
controllers 21-1..21-3, the scheduler determines which of
the K transmission channels is preferably scheduled for

the transmission of matrix modulated data symbols, so
that the BER of said transmission is as low as possible.
This scheduling is at least partially based on the CQIs
as calculated by said instance 23. However, it may be
imagined that, although the CQI_1 of transmission channel
$k=1$ is larger than the CQI_2 of a transmission channel
$k=2$, a data packet in data packet buffer 20-2 which is
associated with transmission channel $k=2$ is matrix
modulated and transmitted, because said data packet is
more urgent than the data packets in the data packet
buffer 20-1 that is associated with transmission channel
$k=1$. The results of the scheduling is signalled to the
corresponding buffer controller 21-1..21-3 which then
forwards a data packet to the matrix modulator 26 for
matrix modulation and transmission.

The invention has been described above by means of
preferred embodiments. It should be noted that there are
alternative ways and variations which are obvious to a
skilled person in the art and can be implemented without
deviating from the scope and spirit of the appended
claims. In particular, the proposed CQIs can be used as a
part in any scheduling algorithm that operates in a
MIMO/MISO system, where link-specific information is
taken into account when scheduling. The proposed CQI work
for any non-orthonormal MIMO or MISO transmission
scheme. The proposed algorithms work in any concatenated
feedback/beamforming scheme, with any duplexing
(FDD/TDD/mixed), multiple access (CDMA,TDMA,SDMA,OFDMA)
single carrier/multicarrier (MC-CDMA/OFDMA) system. Any
channel code (trellis, convolutional, turbo, block, LDPC,
TCM), any modulation (PAM, PSK, QAM, higher dimensional
spherical/lattice) and joint/separate channel
coding/space-time coding/modulation, joint/separate

detection/decoding (linear, decorrelating, LMMSE, maximum likelihood, reduced search maximum likelihood, sphere) can be used. The only requirement may be that at some stage the transmission can be described by a vector (in non-orthogonal spatial resources) or a matrix (in non-orthogonal spatial and substantially orthogonal resources) that is actually transmitted from the non-orthogonal spatial resources (antennas/beams/polarizations) and substantially orthogonal resources (time, frequency, subcarrier, code, spatial/polarization eigenmodes).